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Distribution of $E2$ strength in ^{28}Si below 50 MeV excitation energy

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Inelastic electron scattering in ^{28}Si between 4 and 50 MeV excitation energy reveals two concentrations of $E2$ strength in the continuum. One is between 15 and 20 MeV, with a peak at 17 MeV, and can be identified with the giant quadrupole resonance in the ground state oblate well. A broad distribution of $E2$ strength between 22 and 42 MeV is predominantly isovector in nature. In addition, a small but persistent $E2$ peak at 24 MeV was found, which may be interpreted as being the corresponding state in the prolate well to the 17 MeV resonance. It is shown that 50% or more of the photon cross section in excess of the classical dipole sum rule between 10 MeV and the pion threshold may be due to $E2$ absorption.

NUCLEAR REACTIONS $^{28}\text{Si}(e, e')$, $E_0 = 92$ MeV. Measured $d^2\sigma/d\Omega dE_x$, bound and continuum states. Deduced multipolarity λ , reduced matrix element $B(E\lambda)$, sum rule exhaustion.

I. INTRODUCTION

This work was initially undertaken for two reasons: (1) to locate the $E2$ isovector strength in a light nucleus, and (2) to investigate the distribution of the $E2$ isoscalar strength. While an isovector $E2$ resonance which exhausts more than 50% of the sum rule is well established at $130A^{-1/3}$ MeV in heavy nuclei,^{1,2} its strength is apparently dispersed in a nonresonant background or pushed up to higher excitation energy in lighter ones.³ The lightest nucleus in which $E2$ strength in the isovector region has been found in resonant form is ^{58}Ni , where it exhausts approximately 50% of the sum rule.⁴

Secondly, the isoscalar $E2$ resonance is of considerable interest in ^{28}Si because of the coexistence of an oblate and a prolate well,⁵ separated by a (perhaps) spherical barrier of 29 MeV (Ref. 6) and a recent observation in electrofission⁷ of a several MeV wide state at 28 MeV, which could be the prolate counterpart of the oblate giant $E2$ resonance reported by (α, α') at 20 MeV.⁸⁻¹⁰ An additional reason to choose ^{28}Si is the existence of reliable total photon absorption data on the $E1$ cross section¹¹ which can be used to remove the $E1$ cross section from the (e, e') data, leaving mainly $E2$ at low momentum transfer.

II. EXPERIMENTAL DETAILS

Electron scattering spectra were obtained with 91.2 MeV electrons from the 120 MeV linear ac-

celerator of the Naval Postgraduate School, using self-supporting natural Si targets (98% ^{28}Si) of semiconductor quality. The scattering angles were 60, 75, 90, 105, and 120°, corresponding to an elastic momentum transfer from 0.46 to 0.81 fm⁻¹, a range which favors the excitation of $E1$ and $E2$ transitions.

The scattered electrons were momentum analyzed in a 40 cm magnetic spectrometer and detected in a ten scintillation counter ladder in the focal plane of the spectrometer. The 105° and 120° spectra, sorted into 0.1 MeV wide bins, equal to the stepping width of the spectrometer, are shown in Fig. 1. Further details about the experimental setup used have been given recently.¹²

The inelastic cross sections were measured relative to the elastic ones to eliminate systematic uncertainties from target inhomogeneities, solid angle determination, detector efficiency, etc. The elastic cross sections, in turn, can be calculated from the known nuclear ground state charge distribution.

The whole excitation range covered, (4–51) MeV, was measured with a wider stepping width, 2 MeV, before and after each inelastic run to have a possibility to check on background drifts, etc. None were found except for the 75° run, which was taken at too high a count rate below 20 MeV, where the radiation tail is on its rising part.

The resolution was kept to 0.5%, because extensive tests have shown that this value is the optimal compromise between background produced at the energy defining slit system, which raises with

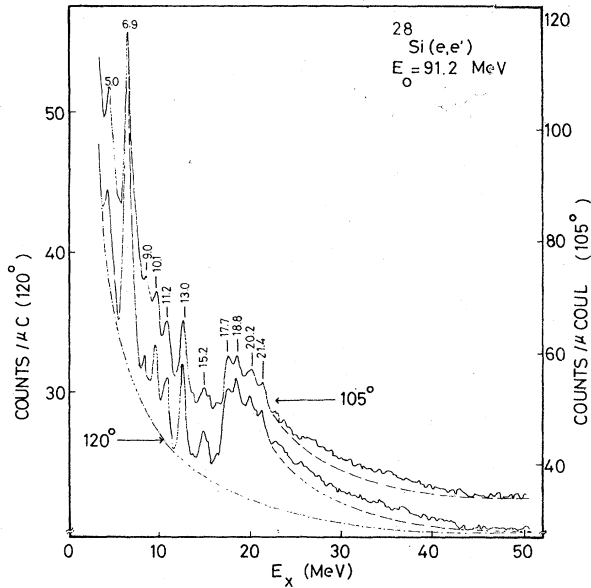


FIG. 1. Spectra of 91.2 MeV electrons scattered from ^{28}Si at 105° and 120° . The dash-dotted line under the 120° spectrum is the maximum background possible, established with a method similar to the one used in (α, α') . The dashed lines beyond 22 MeV were extrapolated from the (γ, abs) data and indicate the "excess" (presumably isovector $E2$) cross section in the region 22–50 MeV. The spectra have been drawn in a way that the peaks (of the peaks) at 6.9 MeV coincide. Its prominent rise from 105° to 120° , compared to the others, is indicative of its $E3$ character. These spectra have not been corrected for the constant dispersion of the magnetic spectrometer.

narrower slits, and background produced in the beam pipes leading to the spectrometer, which raises and is more erratic with wider slits.

III. EVALUATION AND RESULTS

A. General

The elastic cross sections, needed to normalize the inelastic ones as described earlier, were calculated with a phase shift program¹³ using Fermi ground state charge distribution values $c=3.113$ fm and $t=2.377$ fm derived by averaging the values in the tabulation of de Jager *et al.*¹⁴ The inelastic strength (B value) was determined through comparison of experimental cross sections with multipolarity sensitive distorted-wave Born-approximation (DWBA) calculations¹⁵ based on the Myers-Szwiatecki¹⁶ model (see below) for the $E1$ and the Tassie model¹⁷ for higher multipolarities. Except for some modification in the determination of the background we followed the procedure outlined in Sec. IIIA of Ref. 12 including definitions of B values, sum rules, etc. For the sum rule calcula-

tion $\langle R^2 \rangle = 11.3 \text{ fm}^2$ and $\langle R^4 \rangle = 137.7 \text{ fm}^4$ were used.

Various methods are possible for evaluation of the spectra. They all require removal of the radiation tail in one way or another. We found that in ^{28}Si the radiation tail calculations described recently¹² do not match the "true" (that is, a reasonable) background any better than in heavier nuclei such as ^{89}Y . Above 20 MeV calculated and real background diverge rapidly. We therefore did not use either of the alternative methods used for the evaluation of ^{20}Ne ,¹⁸ nor a line shape fit,¹² but something in between which fitted the background, as described in Sec. IIIC, but no resonances.

It is difficult in a nucleus such as ^{28}Si where the continuum $E2$ strength is distributed and not concentrated in a single coherent resonance to assign strength to either isoscalar or isovector resonances. Some guidance can be gained from (α, α') experiments⁸⁻¹⁰ which excite predominantly isoscalar excitations, and theoretical calculations.¹⁹ Not much isoscalar strength should therefore be expected above 20 to 25 MeV. For reasons evident in Sec. IIIC below, we have counted all strength below 20 MeV as isoscalar, except as noted.

B. States below 15 MeV

A line shape fit was thought adequate for evaluating the areas under the clearly visible states below 15 MeV (Fig. 1).

A background function $\text{BGR}(E_f) = p_1 + p_2/E_f + \text{RT}$ was fitted to these low-lying groups of isolated levels (E_f energy of the outgoing electron, RT radiation tail; for particulars see Ref. 12). In this manner the spectra could only be evaluated up to 14 MeV excitation energy. It is clear from the level scheme²⁰ that there are many more levels than those seen by us. However, our momentum transfer favors multipolarities 1 and 2; even $E3$ will be difficult to excite except for very collective states. Furthermore, all states used in our fits were very consistent in excitation energy. If higher multipolarities ($\lambda \geq 4$) would contribute appreciably, this should show in the form factor at the highest momentum transfer and in a systematic shift of the excitation energy. As a test for the validity of the underlying assumption, we may mention that the overall $E2$ strength between 10 and 13 MeV agrees well with the strength from (e, e') with much better (<50 keV) resolution.²¹

With the exception of the 6.9 MeV state all states visible in Fig. 1 (at 5.0, 9.0, 10.1, 11.2, and 13.0 MeV) were found to be predominantly $E2$, contributing 16% to the isoscalar energy-weighted sum rule (EWSR). The form factors for the 10.1 and 13.0 MeV states are shown in Fig. 2. The

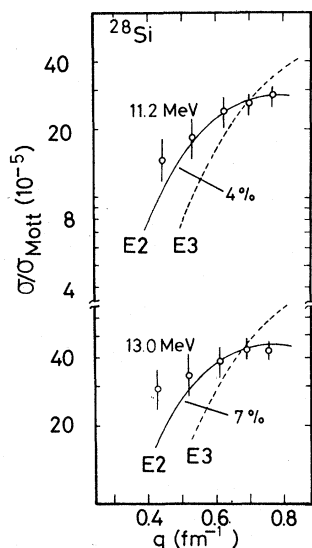


FIG. 2. The cross section divided by the Mott cross section for the states (or group of states) at 11.2 and 13.0 MeV. Comparison with a DWBA calculation based on the Tassie (identical with the Goldhaber-Teller) model and normalized to the percentage exhaustion of the isoscalar EWSR as indicated shows clearly that these states are quadrupole excitations.

6.9 MeV state clearly follows an E3 form factor (Fig. 3) and exhausts 22% of the isoscalar E3 EWSR, that is, all the strength expected in a schematic model for the $1\hbar\omega$ E3 transition.²²

A state with a larger width was found at 15 MeV and had to be treated differently. The (γ, abs) data from Ahrens *et al.*¹¹ show clustered E1 strength (Fig. 4), which complicates evaluation of other strength which may be present. Subtraction of the E1 strength in this region, described in

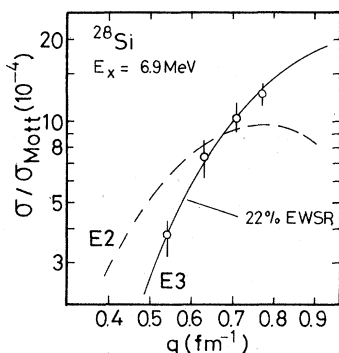


FIG. 3. Similar to Fig. 2 but for the level at 6.9 MeV. Comparison with DWBA calculations shows this state to be E3. This state agrees very well with the $1\hbar\omega_0$ isoscalar E3 state predicted by the shell model at $24A^{-1/3}$ MeV with a strength of 28% of the EWSR ($\Delta T=0$) (see Ref. 22).

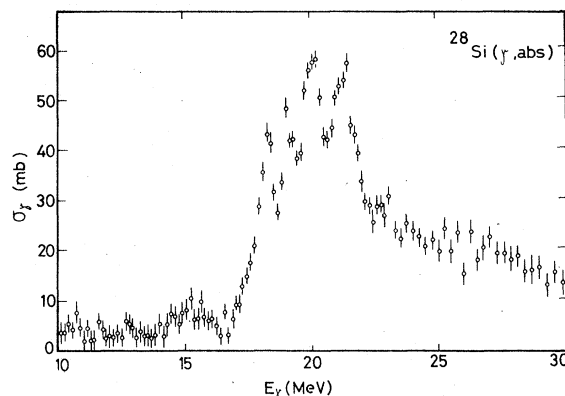


FIG. 4. Total photon absorption data of Ref. 11. The data were averaged into ~ 1 MeV wide bins and subtracted from the similarly averaged electron scattering spectra; see text.

more detail below, from our data indicates 7% isoscalar E2 strength between 14 and 16 MeV. For bookkeeping purposes we have divided this strength, counting half of it in the region below 15 MeV and the other half between 15 and 30 MeV (next section). Inclusion of the E0 state reported¹⁰ at 15.9 in the analysis would not substantially alter our results, because its strength, expressed as a fraction of the E2 sum rule, would only be about 1%. Together with the first excited 2^+ state at 1.78 MeV, which exhausts 10% of the isoscalar EWSR,²⁰ 30% of the E2 ($\Delta T=0$) strength is exhausted below the giant resonance region, in good agreement with α -capture experiments,² and comparable to measurements^{23,9} in ^{24}Mg and ^{20}Ne (Ref. 18), but somewhat higher than the (α, α') results of Van der Borg *et al.*¹⁰ in ^{28}Si , who report approximately 20% EWSR below 15 MeV.

C. E2 strength in the 15 to 30 MeV region

1. General

In the region between 15 and 30 MeV the line shape evaluation¹² was modified due to the fragmentation of the continuum strength into many levels in a light nucleus such as ^{28}Si . The following procedure was employed to determine the background.

Our reasoning is that using the very restricted background described in Sec. IIIB, fitting it to describe the lines below 15 MeV and forcing it to describe the E1 cross section between 45 and 50 MeV, known from the (γ, abs) measurements, an acceptable background could be established in the region below 30 MeV. This method assumes that only the E1 cross section is present at 45–50 MeV. We will come back to this point in the next section, but two alternate methods of fixing the background

at 50 MeV resulted in only minimal changes below 30 MeV. As in heavier nuclei, the radiation tail alone does not satisfactorily describe the background beyond 20 to 25 MeV.

Figure 5 shows the total measured range of the 105° and 120° spectra after background subtraction. The data below 30 MeV were averaged into ~1 MeV wide energy bins (Fig. 6, upper curve with full circles). The similarly averaged total photon absorption data were converted to equivalent (e, e') E1 cross section (Fig. 6, curve without circles)²⁴ using the model developed by Myers *et al.*¹⁶ based on the droplet model.²⁵ The E1 cross section finally was subtracted from the (e, e') data, resulting in the lowest (fat) curve in Fig. 6.

Figure 7 shows that the choice of the model for the conversion from (γ, abs) can influence the result. Our choice was based on concurrent measurements in ^{58,60}Ni and ¹⁴⁰Ce which showed that the Myers-Swiatecki (MS) model is in better agreement with the (e, e') cross sections in these nuclei than either Goldhaber-Teller²⁶ or Steinwedel-Jensen²⁷ models. The MS model describes the transition charge density for the giant dipole

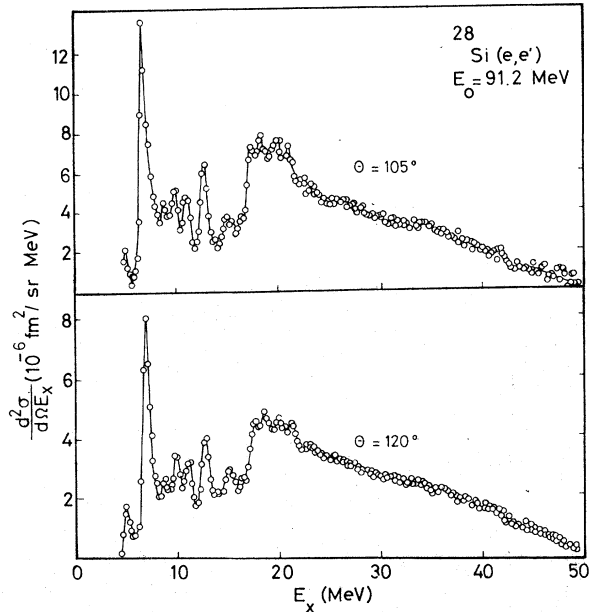


FIG. 5. Data of Fig. 1 after subtraction of a background described in the text and correction for the constant dispersion of the magnetic spectrometer. Some similarity to the photon data of Fig. 4 in the 17 to 22 MeV region can be recognized, especially the four characteristic peaks at 17.7, 18.8, 20.2, and 21.4 MeV. The ghost peak located at 92% of the elastic energy ($E_x = 7.3$ MeV) has been subtracted. The spectra were taken and fitted with 10 points per MeV, which have been reduced by a factor of 2 for graphical purposes. The statistical error is equal to the size of the circles in the 120° spectrum and slightly larger for 105°.

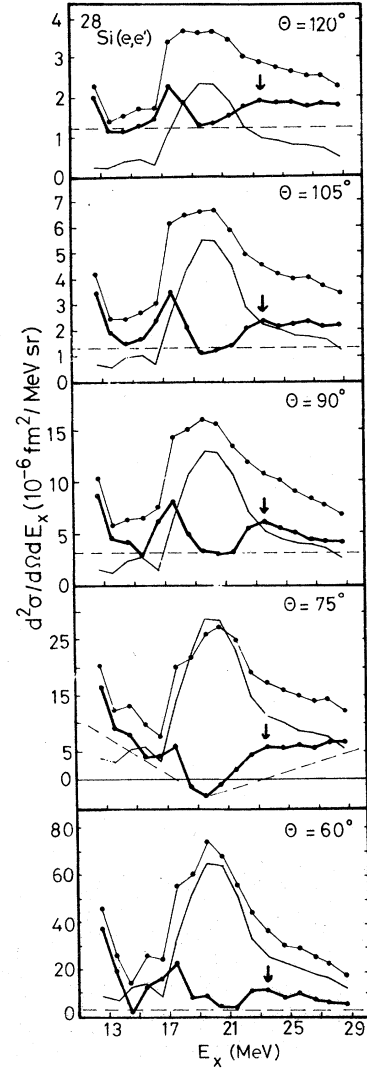


FIG. 6. All data of this experiment between 13 and 29 MeV after subtraction of a background described in the text and averaging into ~1 MeV bins. The top-most line with dots represents the data as shown in Fig. 5 for 120 and 105°, the middle curve without dots the (γ, abs) cross section after conversion to (e, e') cross section, and the lowest fat line with dots the difference. The dashed lines show the background used for one version of the analysis. Other salient features of this figure are discussed in the text. However, we would like to point out that the pointed peak in the top curve at 60° becomes broader and broader with rising angle until it is a several MeV wide plateau at 120°. This change indicates a growing contribution of multipolarities different from E1 on both shoulders of the GDR (Fig. 4) and cannot be produced by any type of background used in the analysis. The 24 MeV peak is indicated by arrows.

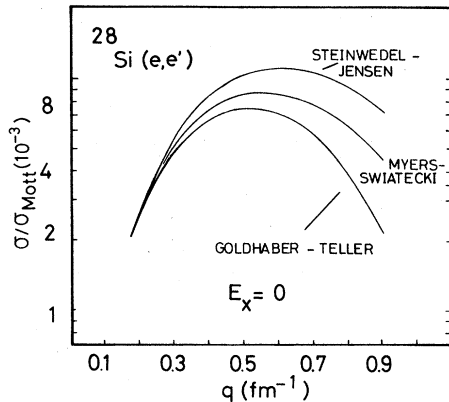


FIG. 7. Comparison of DWBA calculations based on the three models indicated. It is evident that, e.g., use of the Goldhaber-Teller model instead of the Myers-Swiatecki model would influence the quantitative results because the relative difference $[\sigma(\text{MS}) - \sigma(\text{GT})]/\sigma(\text{MS})$ changes from 8% for 60° to 28% for 120° , lowering the $E1$ strength subtracted by approximately 20%. However, measurements in other nuclei indicate that the MS model describes the GDR better, and, furthermore, the qualitative features do not change no matter what model is used.

resonance (GDR) in terms of GT and SJ models in the following form:

$$\rho_{\text{tr}}^{\text{MS}}(r) = \frac{C^{\text{MS}}}{1 + \alpha} [\rho_{\text{tr}}^{\text{GT}}(r) + \alpha \rho_{\text{tr}}^{\text{SJ}}(r)]$$

with $\alpha = 0.44$ in ^{28}Si for the droplet mode.¹⁶

Unfortunately the (γ, abs) results are reliable in detail only up to 30 MeV, owing to coherent pair production at higher energy¹¹ and this method is therefore possible only for this limited energy range. However, we have assumed that the integrated strength up to the pion threshold given in earlier publications^{28,29} is roughly correct. It should be noted that the (γ, abs) cross section (Fig. 4) which was subtracted from our data to get the $E2$ (and $E3$) cross section contains $E2$ strength itself, but the magnitude of this strength below 30 MeV is small compared to the estimated error in background determination and the γ - $E1$ cross section, since the $E2$ contribution is proportional to E_x^3 (Ref. 24). The $E2$ contribution changes therefore rapidly with rising excitation energy and we will return to this point further below.

Before we discuss the results shown in Fig. 6, we want to point out what can go wrong with this type of analysis. The radiation tail described the apparent background quite well up to 20 MeV and reproduced the general form of the spectra over the full range (up to 51 MeV). We were therefore able to use the very constrained form described

above for BGR with only two free fitting parameters. A polynomial fit of the background, in contrast, would need 7 to 9 parameters to achieve a 1% accuracy. What is problematic is the height of the background, that is, mainly the constant term P_1 . Since the background is not only smooth, but moreover of constant concavity, it is difficult to imagine that this method would produce any structure in the $E2$ cross section shown in Fig. 6 which is not genuinely there. What is easily possible, however, is a shift of the (assumed to be constant) baseline. Similarly, even if the $E1$ cross section should be different from the one we used (MS model), these differences will be a smooth function of both excitation energy and angle, again introducing in first order some kind of baseline shift in the form factors. If one adjusts the baseline in the spectra of Fig. 6 in such a way that it goes through the lowest points of the $E2$ cross section, minimum values for the $E2$ strength are established. The baselines thus constructed are shown with broken lines in Fig. 6. Further justification for adjusting the baseline may be drawn from the fact that the lowest points in the $E2$ cross sections at 90° , 105° , and 120° , where the $E2$ is reasonably strong, have approximately the same height on both sides of the 17.5 MeV peak. In addition, the adjustment of the baseline makes our evaluation

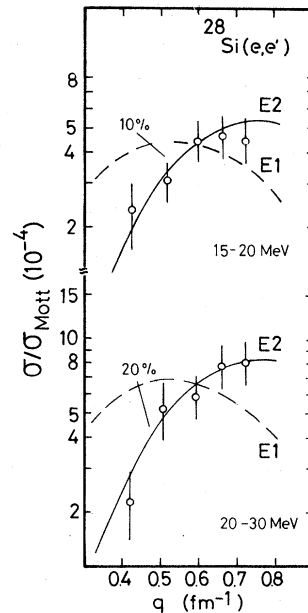


FIG. 8. Comparison of (e, e') strength between 15 and 20 and 20 to 30 MeV with DWBA calculations based on the MS model for the $E1$ and the GT model for the $E2$. The data correspond to the R_{min} values of Table I, but the 15 to 20 MeV data do not include half of the $E2$ strength found between 14 and 16 MeV.

compatible with methods of evaluation generally applied in (α, α') , an essential condition for any comparison.

Independent of these considerations, Fig. 6 shows the following features: (1) a clustering of strength around 17.5 MeV with a width of several MeV, (2) a minimum at 20 MeV, (3) a raise at 22 MeV, and (4) a flat plateau beyond 23 MeV. In addition, a small but persistent and consistent maximum at 24 MeV is evident.

Figure 6 invites a separate treatment of the 15 to 20 and 20 to 30 MeV regions because they are clearly separated by a valley at 20 to 22 MeV. Figure 8 shows that the remaining cross section after subtraction of the $E1$ in both regions follows an $E2$ form factor.

2. The 15-20 MeV complex

In contrast to heavier nuclei, no isoscalar $E2$ strength was initially observed at an excitation energy of $63A^{-1/3}$ MeV in light nuclei with α 's of 96 MeV.³⁰ In the meantime several α -scattering experiments have investigated this region with higher primary energy and have shown that a highly structured $E2$ giant "resonance" exists, which peaks between 19 and 20 MeV in (α, α') and exhausts between 25 and 30% of the energy-weighted sum rule (Table I).⁸⁻¹⁰ This strength agrees very well with the value derived from our evaluation with unadjusted baseline, $(26 \pm 5)\%$. However, as pointed out above, this analysis is inconsistent with the analysis used in (α, α') , where, due to

TABLE I. Distribution of $E2$ strength in ^{28}Si into the various regions discussed in the text. Although isospin cannot be directly inferred from (e, e') , the strength below 20 MeV should be predominantly isoscalar and the one above isovector, based on macroscopic and microscopic considerations and comparison with heavier nuclei. The subscripts max and min refer to maximum and minimum values of the sum rule extracted under the background assumptions discussed in the text, ΔR shows the error (in %) if one does not take into account contributions to the error from the background assumptions.

E_x (MeV)	R_{max}^a	R_{min}^a	ΔR (%)
0-15	30 ^b	30 ^b	10
15-20	26 ^b	14 ^b	20
20-30	32	10	20
30-50	70	50	30
	50 ^c	30 ^c	

^a $R = E_x B(E2)/\text{EWSR}(E2, \Delta T = 0, 1) \times 100$.

^bIncludes 3.5% EWSR from 14-16 MeV complex.

^cLower value derived by assuming 70% of isoscalar $3\hbar\omega_0 E3$ strength between 30 and 50 MeV (Ref. 22).

the lack of knowledge about the nuclear background, an arbitrary (usually linear^{8,9} but sometimes curved¹⁰) background is adjusted to smoothly connect to the nonresonant cross section on both sides of a visible resonance.

The value consistent with the (α, α') assumptions about the background is $(14 \pm 3)\%$ EWSR (Table II). This result then is in disagreement with the α experiments quoted,⁸⁻¹⁰ measurements, in which no $E1$ was believed to be excited, but not to the (p, p') results, $(15 \pm 5)\%$, where the GDR has been taken into account¹⁰ [the (p, p') value reduces to $(12 \pm 4)\%$ if one uses, for consistency, the Myers-Swiiatecki model instead of the Goldhaber-Teller model, as outlined above, to subtract the $E1$ strength]. In addition, from visual inspection of the (α, α') spectra and comparison with Fig. 6 we conclude that apart from the sum rule exhaustion the $E2$ distribution is not in agreement with ours, namely it is centered 2 MeV higher. In contrast, our overall strength distribution, peaking around 17 MeV, is in agreement with α capture.²

A possible explanation comes from α capture on ^{24}Mg (Ref. 31), where sizable isospin impurities ($T=0$) have been reported in the lower part of the GDR of ^{28}Si , but not above approximately 20 MeV. It has been shown that relatively small $T=0$ amplitudes in the GDR cross section (20%) can give rise to rather dramatic effects.³² Inelastic α scattering would excite these impurities, thus shifting the center of gravity of the apparent $E2$ cross section. This could also explain why in ^{28}Si Knöpfle *et al.*⁸ had to choose a background different from other

TABLE II. Comparison of the strength of the isoscalar $E2$ resonance around 17 to 20 MeV from various reactions. It is evident that the strength is grouped around two values, (12 to 14)% and (25 to 31)% of the isoscalar sum rule. As outlined in the text the higher value in hadronic experiments is from measurements where the $E1$ was not taken into consideration. If we use the equivalent background procedure as in (α, α') , the lower value of $(14 \pm 3)\%$ EWSR results.

E_x (MeV)	Reaction	R^a	Reference
16.9-24.8	(α, α')	31 ± 5	Knö76
15.5-23.0	(α, α')	27 ± 6	VanB77
	(p, p')	12 ± 4^b	
~ 19.4	(α, α')	~ 25	YouR77
15-22	$^{24}\text{Mg}(\alpha, \gamma)$	~ 13	Han76
15-20	(e, e')	26 ± 5^c	this
		14 ± 3^d	work

^a $R = E_x B(E2)/\text{EWSR}(E2, \Delta T = 0) \times 100$.

^bValue corrected for Myers-Swiiatecki model.

^cIncluding nonresonant strength.

^dBackground consistent with (α, α') .

nuclei to fit the E2 angular distribution and Van der Borg *et al.*¹⁰ had to use a curved background. Youngblood *et al.* only measured at two angles from which they estimated the E2 strength. Moreover, Yang *et al.*²³ have shown with high resolution (α, α') at 70 MeV that E1 states in ^{24}Mg at 9.15, 11.46, and 11.8 MeV are excited appreciably. Since no E1 sum rule strength is given, we have estimated an upper limit from electron scattering for the 9.15 MeV state, which is framed by two E2 states at 9.0 and 9.28 MeV. They are presumably identical with the E2 states at 8.99 and 9.30 MeV measured with (e, e') by Titze.³³ In the latter measurement the momentum transfer was such that the E1 form factor is on the top of the first maximum. From the known electromagnetic strength of the two E2 states, $B(E2, 8.99) = 3.6 \text{ fm}^4$ and $B(E2, 9.30) = 11.2 \text{ fm}^4$, an upper limit can be placed on the strength of the E1 state at 9.15 MeV, namely 0.1% of the classical dipole sum rule³⁴ [Thomas-Reiche-Kuhn (TRK)] because otherwise it should have been seen in (e, e'). In comparison, the 8.99 MeV E2 level exhausts 0.5% of the E2 isoscalar EWSR, but appears much weaker in (α, α') (its peak height is even less than $\frac{1}{2}$ of that of the E1 state, but one has to take into consideration that at the angle shown in Fig. 1 of Ref. 23, 17° , the E1 is at a relative maximum, while the E2 is in a minimum). A quantitative estimate using the E1 strength between 15 and 20 MeV from Ref. 28, 30% EWSR, and the ratio of the $T=0$ to $T=1$ amplitude given by Wu, *et al.*³², 15%, shows together with the order of magnitude estimate on the basis of Ref. 23 that the assumption of 10% of the E2 strength in Refs. 8, 9, and 10, in reality being due to E1 $T=0$ admixtures to the GDR, is not inconsistent with the data.

Finally, comparing the (α, α') data on ^{28}Si which have the best resolution, those of Van der Borg *et al.*¹⁰ with the total γ -absorption data of Ahrens *et al.*¹¹ one finds an energy correlation between some of those complexes believed to have an E3 contribution (18.8, 20.2, and 21.5 MeV) and the peaks of (γ, abs). Since the odd multipolarities E1 and E3 would track with the same phase and the angular distributions are similar except for very forward angles, it is well possible that the assumed E3 contribution is in reality E1.

Naturally, what we have presented above as evidence for an E1 cross section in the giant quadrupole resonance (GQR) in (α, α') is only circumstantial. We think, however, it justifies a more detailed investigation. Measurements^{35,36} in heavier nuclei ($A \lesssim 52$) also indicate that $\Delta T=0$ isospin impurities may play a more important role in the excitation of the GDR than has been taken into account to date in (α, α').

3. The 20-30 MeV complex

This energy range contains the rise in cross section around 22 MeV and the 24 MeV peak which sits on top of the level E2 distribution above 23 MeV.

The difference in excitation energy between the 17.5 MeV E2 strength and the 24 MeV peak lends itself to the following interpretation: The 17.5 MeV state may safely be assumed to be an isoscalar giant quadrupole resonance built upon the oblate ground state. The 24 MeV state then is the corresponding mode in the prolate well. We want to emphasize that this interpretation is based mainly on the energy difference between the two peaks, 6.5 MeV, which compares well with the 6.7 MeV assumed to be the difference between the wells^{5,6} as inferred from the excitation energy of the second 0^+ state in ^{28}Si , 6.7 MeV, which being much weaker than the first 0^+ state³⁷ has been interpreted as the ground state of the prolate shape.⁷ In addition, shell model calculations by Hecht and Braunschweig,³⁸ using symmetry arguments to select the probable components of an E2 giant resonance built upon the 6.7 MeV 0^+ state, predict this state to be between 19–22 MeV. This value is still somewhat lower than the 24 MeV we find, but it is in better agreement than the 28.3 MeV peak of Ref. 7.

While our result does not corroborate the conclusion by Sandorfi *et al.* that the 2 MeV wide 28 MeV peak seen in the ^{12}C channel in electrofission of ^{28}Si is due to excitations of the GQR in the prolate well, because we do not see such peak, it does not contradict it either on purely experimental grounds. The strength from ^{28}Si (e, f) was⁷ 0.16 $\Gamma/\Gamma_{12C}\%$ EWSR (E2). From Fig. 6 an upper limit on E2 strength concentrated into a 2 MeV wide peak in our measurement can be given in the following way. The total E2 strength between 20 and 30 MeV is 10% EWSR (minimal value, Table I). The peak at 24 MeV, which is just marginally visible, has a height of about $\frac{1}{5}$ of the height of the cross section above the dashed line, resulting in 0.2% EWSR/MeV as upper limit, that is, a 2 MeV wide resonance should be visible if larger 0.4% EWSR. On the other hand, this places an upper limit of $\Gamma/\Gamma_{12C} < 2.5$ on the branching ratio, but only if the peak at 28 MeV is isolated on a flat "background." By the same method we derive a lower limit for the 24 MeV peak of $\sim 0.5\%$ isoscalar EWSR. This value would be in rough agreement with the estimate one may make for (α, α') E2 strength at 24 MeV, based on Fig. 4 of Ref. 9 and Fig. 1 of Ref. 8 if one assumes all the strength between 23 and 25 MeV to be E2. A strength estimate in the case of Ref. 10 is difficult, due to the

curved background used by the authors and the limited statistical accuracy, the price to pay for the very good resolution achieved in this experiment.

It is difficult to make more quantitative arguments about whether or not the ratio of the strength of the GQR in the prolate and oblate well is correct because not much attention has been paid to the nature of the barrier between the two wells of different deformation. Castel and Svenne⁶ calculate 29 MeV for the height of a spherical barrier between oblate and prolate shape, but they also note that the transition could go through a triaxial shape, resulting in a lower barrier; a schematic diagram is shown in Fig. 9. The rapid rise of the $E2$ cross section at 22 MeV may thus be interpreted as an indication that the barrier is indeed triaxial and not spherical.

It seems unlikely that all the $E2$ strength between 20 and 30 is due to the prolate well. Consequently one would have to assume that most of the underlying $E2$ strength between 22 and 30 MeV is isovector strength, which is corroborated by the nonexcitation of most of this strength in (α, α') .

Additionally, it is evident from the extrapolation of $E1$ strength in Fig. 1 (broken lines) that "excess" cross section is present out to 45 MeV. The centroid of this excess cross section, at 33 MeV, corresponds to $100A^{-1/3}$ compared to $135A^{-1/3}$ for isovector strength in heavy nuclei.¹ This lowering of the isovector state corresponds quite well to the

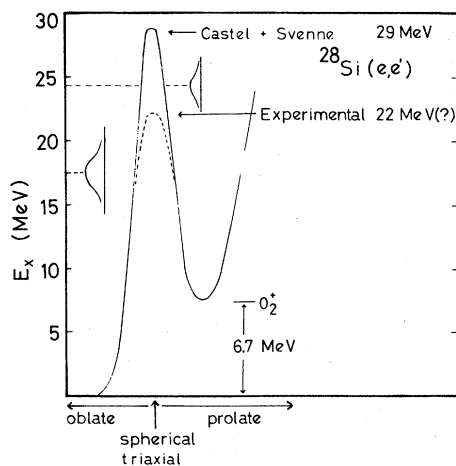


FIG. 9. Schematic presentation of oblate (ground state) and prolate (build up on the 6.7 MeV 0^+ state) well in ^{28}Si . The height of the spherical barrier, 29 MeV, has been taken from Ref. 6; 22 MeV is a barrier height which could be inferred from the 24 MeV peak in our data. If one were (Ref. 6) to follow the arguments by Castel and Svenne (Ref. 6) this lower barrier would be indicative for a triaxial transition deformation between the oblate and prolate well.

lowering of the $E1$ resonance from $80A^{-1/3}$ MeV in heavy nuclei to $65A^{-1/3}$ in ^{28}Si .

Again, as in the previous section, we give a high and a low value for the $E2$ strength. The high one, 32%, corresponds to the strict application of the background subtraction, while the low one, 10%, is based on the dashed line in Fig. 6 and corresponds to the cross section above the dashed lines in Fig. 1 as well.

It is unfortunate that the problems encountered in the total photon absorption above 30 MeV prevent an extension of the method employed by us below 30 MeV to higher excitation energies, because we think, as discussed above, that isovector strength extends from 22 MeV to 45 MeV, making a unified evaluation of this total region desirable. We will, however, come back to the problem of the total $E2$ strength later.

The question remains to be solved: Which of the background used (high or low) is the correct one? We find a better agreement of the data with an $E2$ form factor for the 15–20 and 20–30 MeV regions with the higher background. The higher one implicitly assumes no nonresonant background to be present. However, form factors based on the lower background are still in agreement, albeit less good, with $E2$. Some help in deciding this problem can be drawn from the (α, α') measurements. The background data of Van der Borg *et al.*¹⁰ show only a weak oscillation characteristic of an even multipolarity cross section in the region of the third $E2$ maximum (Fig. 2 of Ref. 10). An oscillation of about the same height is exhibited in the data of Knöpfle *et al.*,⁸ but appears much more pronounced due to the many more data points taken and the much better statistics. If one assumes that the background angular distribution should not show any structure and decrease monotonically with the angle, as shown for heavier nuclei by Youngblood *et al.*,³⁹ we estimate from Fig. 2 of Ref. 8 that less than 10% of the $E2$ EWSR is hidden in the "background." This estimate has assumed that all of the structure seen in the background angular distribution is due to $E2$, which is probably wrong because the second maximum should show up at least as strong as the third in the background, but is not visible at all. The structure thus seen in the background angular distribution should presumably be interpreted as due to $E4$ excitations (it has to be an even multipolarity because it is in phase with $E2$). An alternative interpretation would have to assume that the empirical background used in Refs. 8 and 10 gets progressively worse with angle.

Weighing all the evidence together we conclude that the lower values given in Table I up to 30 MeV excitation energy are the more realistic ones, and

that there is not as much nonresonant $E2$ strength below 30 MeV as one could conclude from Table I.

On the theoretical side, the most detailed predictions for the distribution of $E2$ strength ^{28}Si have been made by Abgrall *et al.*,¹⁹ predicting a division of the continuum isoscalar strength into two parts. One is centered around 19 MeV and comprises between 50 and 65% of the $E2$ isoscalar EWSR and the second is around 30 MeV, comprising between 13 and 24% of the EWSR, depending on the coupling used. While the lower-lying $E2$ state found in our experiment at 17.5 MeV is definitely much lower in strength than predicted, the strength of the higher isoscalar component predicted could easily be hidden in the isovector strength in (e, e') . Since it also has not been seen in (α, α') , where the isovector $E2$ strength would not interfere that much in its identification if concentrated in a narrow enough energy range, it is probably not there.

D. The region from 30 to 50 MeV

We have reasoned above that using a background with only two free parameters, $\text{BGR}(E_f) = P_1 + P_2/E_f + \text{RT}$, as described in Sec. IV B, and forcing it through a cross section at 50 MeV determined from (γ, abs) measurements, should result in an acceptable background up to 30 MeV, since the radiation tail alone describes the data very well up to 20 to 25 MeV. For the region above 30 MeV we used a slightly different approach, which, however, did not alter the background below 30 MeV. We found that assuming only the $E1$ cross section known from (γ, abs) to be present at 50 MeV led to somewhat inconsistent results, in particular the approach of BGR to the measured cross section at 50 MeV was not as smooth as might be reasonably expected. We therefore fit the region between the mesalike part of the $E1$ resonance and 50 MeV with "filler" resonances. We tried to use the minimum number of such resonances. Three were found sufficient to achieve a $\chi^2 < 1$ (per degree of freedom). We do not give parameters of these "resonances" here because they were not regarded as resonances, that is, as due to a coherent excitation of a certain multipolarity, but as a vehicle to establish a reasonable background. The resulting cross section after subtraction of the background is shown for the 105 and 120° spectra in Fig. 5. Since the $E2$ strength between 22 and 45 MeV is high in excitation energy and spread out over a wide range, it does not show up in the lower momentum transfer measurements. The following discussion is therefore based on the 105 and 120° data alone.

Assuming that the (e, e') cross sections as shown in Fig. 5, after subtraction of the integrated

$E1$ strength between 30 and 50 MeV (~45% TRK sum rule³⁴) from Ref. 28, is entirely $E2$, it exhausts 70% of the isovector $E2$ sum rule. As outlined earlier, we cannot decide between isoscalar and isovector strength and the assignment to either one is merely a matter of convention and convenience. Since this is the region where the $3\hbar\omega$ isoscalar $E3$ strength is located in heavier nuclei, namely $E_x = 110A^{-1/3}$ MeV, corresponding to 36 MeV in ^{28}Si , we have subtracted Hamamoto's estimate of 75% of the $E3$ ($\Delta T = 0$) EWSR²² resulting in a lower limit of 50% of the $E2$ ($\Delta T = 1$) EWSR (Table I). If we were to take into account only the area above the dashed lines in Fig. 1 between 22 and 45 MeV, a sum rule value of 50% $E2$ would be derived without $E3$ subtraction and 30% with $E3$ subtraction. Possible implications of this result will be discussed in the next section.

IV. TOTAL $E2$ STRENGTH AND THE NATURE OF THE PHOTON ABSORPTION CROSS SECTION BELOW THE PION THRESHOLD

Table I shows the contribution of the various regions to the $E2$ sum rule. Since in an $N = Z$ nucleus no distinction is necessary between the actual values of isovector and isoscalar sums, the total sum should be 200%. We have outlined in the foregoing discussion of the results why the lower values seem to be the more reliable ones. If this is correct, the strength is missing and in this section we want to speculate about its whereabouts in conjunction with the (γ, abs) results. But even if the higher values are correct, important conclusions concerning the photon cross section can be drawn. Depending on the assumption of high or low background, and subtraction of $E3$ strength, the missing strength ranges from (30 ± 36) (that is, no strength is missing) to $(106 \pm 18)\%$ of the isovector or isoscalar sum rule.

The photon absorption cross section integrated up to the pion threshold, denoted as $\sigma(140)$, has been an important topic for a long time. The Gell-Mann, Goldberger, Thirring (GGT) sum rule,⁴⁰ based on fundamental assumptions, gives a value of $\sigma(140) = 1.4 \times 60(NZ/A)\text{mb}$, that is, 1.4 times the classical $E1$ sum rule. The 40% excess has been taken as a measure of mesonic contributions below the pion threshold. Much experimental effort^{11,41} has been devoted to measure $\sigma(140)$ with the result $\sigma(140) \approx 2 \times 60 NZ/A$, that is, in excess of the GGT sum rule. This overexhaustion has produced considerable theoretical effort to reconcile the assumption of the GGT sum rule with the data (see, e.g., Ref. 42). While nothing in the derivation of the sum rule prohibits other multipolarities to contribute to $\sigma(140)$, generally it seems to have been assumed that it all is $E1$ in attempts to de-

rive nuclear models which describe the experimental photon cross section at 40 MeV and above (see discussion in Ref. 11).

Table III shows a summary of the possible contribution of $E2$ strength $\sigma(140)$. In calculating Table III it was assumed that for $E_x > 30$ the $E2$ strength was centered in the middle of the energy intervals indicated and distributed with a Breit-Wigner shape with the width of the interval; this strength distribution was integrated up to the pion threshold. Assuming a larger width would not change the contribution. It would push strength into the tails, where it will contribute more strongly according to²⁴

$$\int \sigma_\gamma dE_\gamma = 3.1 \times 10^{-7} E_x^3 B(E\lambda, k),$$

but some of it will be lost above the pion threshold. In total the contribution will rise with an exponent lower than 3 in any case, because of (1) the effect of the energy weighting in the sum rule, and (2) the dependence of the B value on the photon momentum k . We tried various forms and distributions and found only small changes which could not change the basic result.

Why did we assume the missing strength to be at 60 MeV? First, it has to be somewhere above 50 MeV, and choosing 60 MeV gives a lower limit on the strength, and second the (γ, abs) measurements show a pronounced cross section in this region. However, since those measurements for ^{28}Si have been hampered by coherent pair production above 30 MeV because a silicon monocrystal was used,

giving rise to the Überall effect,⁴³ we have also looked into the ^{27}Al results. ^{27}Al should be very similar to ^{28}Si above 30 MeV and, in fact, agrees very well with earlier published ^{28}Si data²⁸ insofar as both measurements show a distinctive cross section at 50–70 MeV. While the observed $E2$ strength between 10 and 30 MeV (45% $E2$ isoscalar EWSR) contributes only approximately 3% to the $E1$ sum rule, this value rises to 6–8% TRK for the 50% $E2$ ($\Delta T = 0, 1$) EWSR between 30 and 50 MeV. If we assume the missing 50% of the $E2$ sum rule to be centered at 60 MeV with the distribution described above, which would not contradict the (γ, abs) data, this strength would make a contribution to the integrated (γ, abs) cross section between 10 and 140 MeV equivalent to 15–25% of the TRK $E1$ sum rule. If we assume it to be even higher, it would contribute even more. It thus seems possible that a major fraction (up to 50%) of the excess strength seen in (γ, abs) is due to $E2$ strength. The $E3$ strength, in contrast, would even under the most favorable reasonable assumptions contribute no more than approximately 10%.

For completeness, we would like to mention that similar considerations applied to the missing $E2$ strength in a concurrent measurement⁴⁴ on ^{141}Ce , when compared to (γ, n) measurements up to $E_\gamma = 100$ MeV at Saclay,⁴¹ lead to similar conclusions.

We want to emphasize, however, that we only have inferred from the missing $E2$ strength that there is the possibility that a large fraction of the photon cross section is of $E2$ nature. Perhaps future (e, e') coincidence experiments up to the meson threshold will be able to decide this problem positively (or negatively).

V. SUMMARY

We have measured ^{28}Si between 4 and 51 MeV excitation energy. Although ^{28}Si poses many interesting problems concerning distribution and fine structure of the $E1$ strength, our measurement was solely directed at the $E2$ distribution. For this purpose the total photon attenuation data were used to subtract the $E1$ strength. While this introduces a model dependence in our analysis, we do not think it changes any of the qualitative conclusions. While the quantitative results are collected in Tables I–III and have been discussed in the text, we want to repeat the salient qualitative points. These are as follows: (1) The $E2$ strength is widely distributed in (a) numerous isoscalar states below 16 MeV, (b) an isoscalar giant resonance with a width of 3 to 4 MeV which peaks at 17.5 MeV, and (c) a nearly constant distribution between 22 and 45 MeV, which is predominantly isovector in nature. (2) A small, but persistent, peak at 24

TABLE III. Contribution of the $E2$ strength found (or assumed) at different excitation energy regions to the equivalent photon cross section. The Breit-Wigner distribution was integrated from 10 MeV to pion threshold (140 MeV), the constant distribution only in the interval. Results for both depend only weakly on the spreading width (see text). It is evident that the equivalent cross section rises steeply with excitation energy. S and T denote the $E2$ integrated cross sections expressed as a percentage of the TRK sum. The entries for the 50–70 and 70–90 MeV are exclusive, i.e. one should not add them together.

E_x (MeV)	R^a	S^b	T^c
10–20	25	≤ 1	
20–30	20	≤ 2	
30–50	50	6	8
50–70	100 ^d	15	25
70–90	100 ^d	20	40

^a $R = E_x B(E2)/\text{EWSR}(E2, \Delta = 0, 1)$.

^bBreit-Wigner distribution for $E2$ strength function.

^cConstant distribution for $E2$ strength function.

^dAssumed strength.

MeV, riding on top or being a part of the 22–45 mesalike distribution, can be interpreted as the prolate well counterpart of the 17.5 MeV resonance. (3) $E2$ strength is missing compared to the $E2$ sum rule. Reasonable assumptions about the $E2$ strength lead to the surprising result that 25% (or more) of the γ cross section integrated up to pion threshold may be due to $E2$. (4) We suspect that

$T=0$ impurities in the GDR are strongly excited by (α, α') and give rise to discrepancies in the $E2$ distribution between (α, α') on the one side, and (e, e') and α capture on the other side.

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